Contract # N00014-14-C-0004

Autonomous Control Modes and Optimized Path Guidance for Shipboard Landing in High Sea States

Progress Report (CDRL A001)

Progress Report for Period: October 10, 2014 to January 9, 2015

PI: Joseph F. Horn
814-865-6434
joehorn@psu.edu
Penn State University

Co-PI: John Tritschler
(301) 995-1637
john.tritschler@navy.mil
AIR-4.3.2.4

Co-PI: Chengjian He
(408) 523-5100
he@flightlab.com
Advanced Rotorcraft Technologies

January 30, 2015

Performing Organization:

The Pennsylvania State University

Department of Aerospace Engineering

231C Hammond Building

University Park, PA 16802

Attn: Joseph F. Horn

Phone: 814-865-6434, Fax: 814-865-7092

Email: joehorn@psu.edu

Prepared under:

Contract Number N00014-14-C-0004
2012 Basic and Applied Research in Sea-Based Aviation
ONR #BAA12-SN-028
CDRL A001

Report Documentation Page					*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE **30 JAN 2015**		2. REPORT TYPE			3. DATES COVERED **10-10-2014 to 09-01-2015**
4. TITLE AND SUBTITLE **Autonomous Control Modes and Optimized Path Guidance for Shipboard Landing in High Sea States**					5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Pennsylvania State University,,Department of Aerospace Engineering,,231C Hammond Building,,University Park,,PA,16802**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**16**	

Report Distribution per CDRLs for Contract No. N00014-14-C-0004

ENCLOSURE NUMBER 1
CONTRACT DATA REQUIREMENTS LIST
INSTRUCTIONS FOR DISTRIBUTION

DISTRIBUTION OF TECHNICAL REPORTS, FINAL REPORT, THEORY AND USER MANUAL FOR SOFTWARE
(A SF 298 must accompany the final report)

		NUMBER OF COPIES	
ADDRESSEE	**DODAAC CODE**	**UNCLASSIFIED / UNLIMITED**	**UNCLASSIFIED/ LIMITED AND CLASSIFIED**
COR: Mr. John Kinzer ONR Code 351 E-Mail: john.kinzer@navy.mil	N00014	1	1
Program Officer: Dr. Judah Milgram ONR Code 351 E-Mail: judah.milgram@navy.mil	N00014	1	1
Program Officer: Ms. Susan Polsky NAVAIR 4.3.2.1 E-Mail: susan.polsky@navy.mil	N00024		
Administrative Contracting Officer* E-Mail: onr_chicago@onr.navy.mil	N62880	1	1
Director, Naval Research Lab Attn: Code 5596 4555 Overlook Avenue, SW Washington, D.C. 20375-5320 E-mail: reports@library.nrl.navy.mil	N00173	1	1
Defense Technical Information Center 8725 John J. Kingman Road STE 0944 Ft. Belvoir, VA 22060-6218 E-mail: tr@dtic.mil	HJ4701	1	1

* Send only a copy of the transmittal letter to the Administrative Contracting Officer; do not send actual reports to the Administrative Contracting Officer.

ELECTRONIC SUBMISSIONS OF TECHNICAL REPORTS IS PREFERRED AND ENCOURAGED. ELECTRONIC SUBMISSION SHOULD BE SENT TO THE E-MAIL ADDRESSES PROVIDED IN THE ABOVE TABLE, HOWEVER PLEASE NOTE THE FOLLOWING:

- Only Unlimited/Unclassified document copies may be submitted by e-mail.
- Unclassified/Limited has restricted distribution and a classified document (whether in its entirety or partially) is to be distributed in accordance with classified material handling procedures.
- Electronic submission to DIRECTOR, NAVAL RESEARCH LAB, shall be unclassified/unlimited reports and 30 pages or less. If unclassified and more than 30 pages,

Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) initiative in Advanced Handling Qualities for Rotorcraft.

Landing a rotorcraft on a moving ship deck and under the influence of the unsteady ship airwake is extremely challenging. In high sea states, gusty conditions, and a degraded visual environment, workload during the landing task begins to approach the limits of a human pilot's capability. It is a similarly demanding task for shipboard launch and recovery of a VTOL UAV. There is a clear need for additional levels of stability and control augmentation and, ultimately, fully autonomous landing (possibly with manual pilot control as a back-up mode for piloted flight). There is also a clear need for advanced flight controls to expand the operational conditions in which safe landings for both manned and unmanned rotorcraft can be performed. For piloted rotorcraft, the current piloting strategies do not even make use of the available couplers and autopilot systems during landing operations. One of the reasons is that, as the deck pitches and rolls in high sea states, the pilot must maneuver aggressively to perform a station-keeping task over the landing spot. The required maneuvering can easily saturate an autopilot that uses a rate limited trim system. For fly-by-wire aircraft, there is evidence that the pilot would simply over-compensate and negate the effectiveness of a translation rate command/position hold control mode. In addition, the pilots can easily over-torque the rotorcraft, especially if they attempt to match the vertical motion of the deck.

This project seeks to develop advanced control law frameworks and design methodologies to provide autonomous landing (or, alternatively, a high level of control augmentation for pilot-in-the-loop landings). The design framework will focus on some of the most critical components of autonomous landing control laws with the objective of improving safety and expanding the operational capability of manned and unmanned rotorcraft. The key components include approach path planning that allows for a maneuvering ship, high performance station-keeping and gust rejection over a landing deck in high winds/sea states, and deck motion feedback algorithms to allow for improved tracking of the desired landing position and timing of final descent.

2. Activities this period

Task 4 – Dynamic Inversion Control Design

Work at Penn State has been directed towards transitioning the Dynamic Inversion (DI) Control Laws (CLAWS) to the Flightlab Control System Graphical Editor (CSGE). PSU has developed scripts in Flightlab to automate generation of linear models and synthesis of inverse model tables. 4^{th} order inverse models are generated from trimmed flight conditions starting at hover up to 160 knots forward speed in 20 kt increments. These are then ported directly to the CSGE control law diagrams as table look ups. Using these scripts, the re-design of the control laws for the various configurations (UAV and H-53 class) will be relatively seamless. In January 2015, the inner loop control laws were completed. The inner loop CLAWS include the following response types: Attitude Command / Attitude Hold control laws in roll and pitch, yaw rate command / turn coordination control laws in yaw, and vertical speed command control laws in the vertical axis. The response types are achieved via feed forward and feedback compensation schemes following the DI design method. Figure 1 shows the top-level CSGE schematic of the inner loop DI controller. The control laws have been tested and shown to have good tracking performance and good stability. Figures 2 and 3, show a response to a yaw doublet input in hover and a longitudinal doublet input at 80 knots forward speed, respectively. The yaw doublet shows a 180° heading

change in each direction. Off-axis coupling is minimal. The aircraft picks up about 2.4 ft/sec lateral speed, but this will be corrected with the outer loop once it is implemented. The pitch doublet shows an acceleration to 102 knots with 10° nose down attitude, followed by a deceleration back to 80 knots with a 10° nose up attitude. The maneuver demonstrates the inversion model scheduling as the aircraft accelerates across airspeeds. There is some significant altitude cross-coupling with a 30 ft altitude change with the large pitch attitude variations. This could be improved with a higher order inverse model or through the outer loop control law. Cross-coupling to other axes is minimal and the response is very stable.

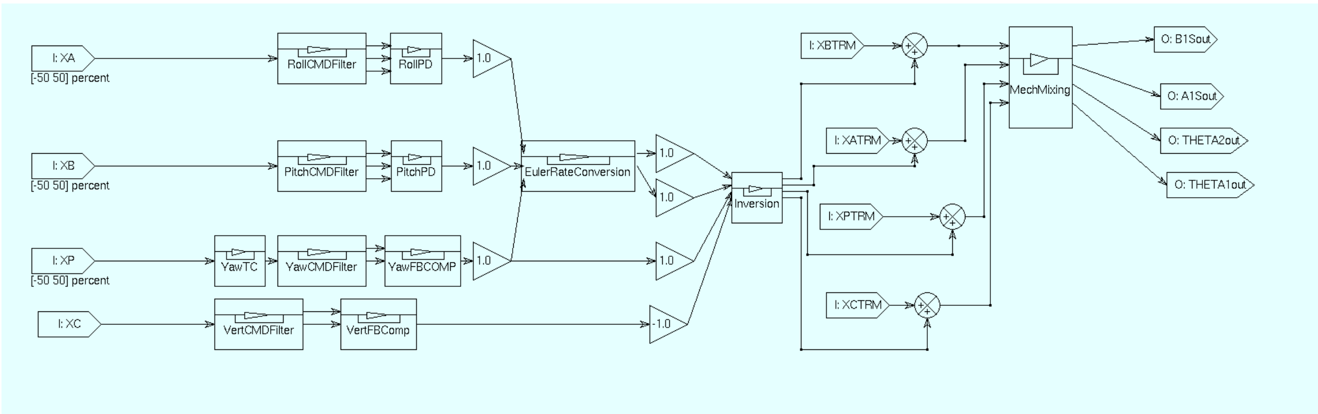


Figure 1 CSGE Diagram of Dynamic Inversion Control Law

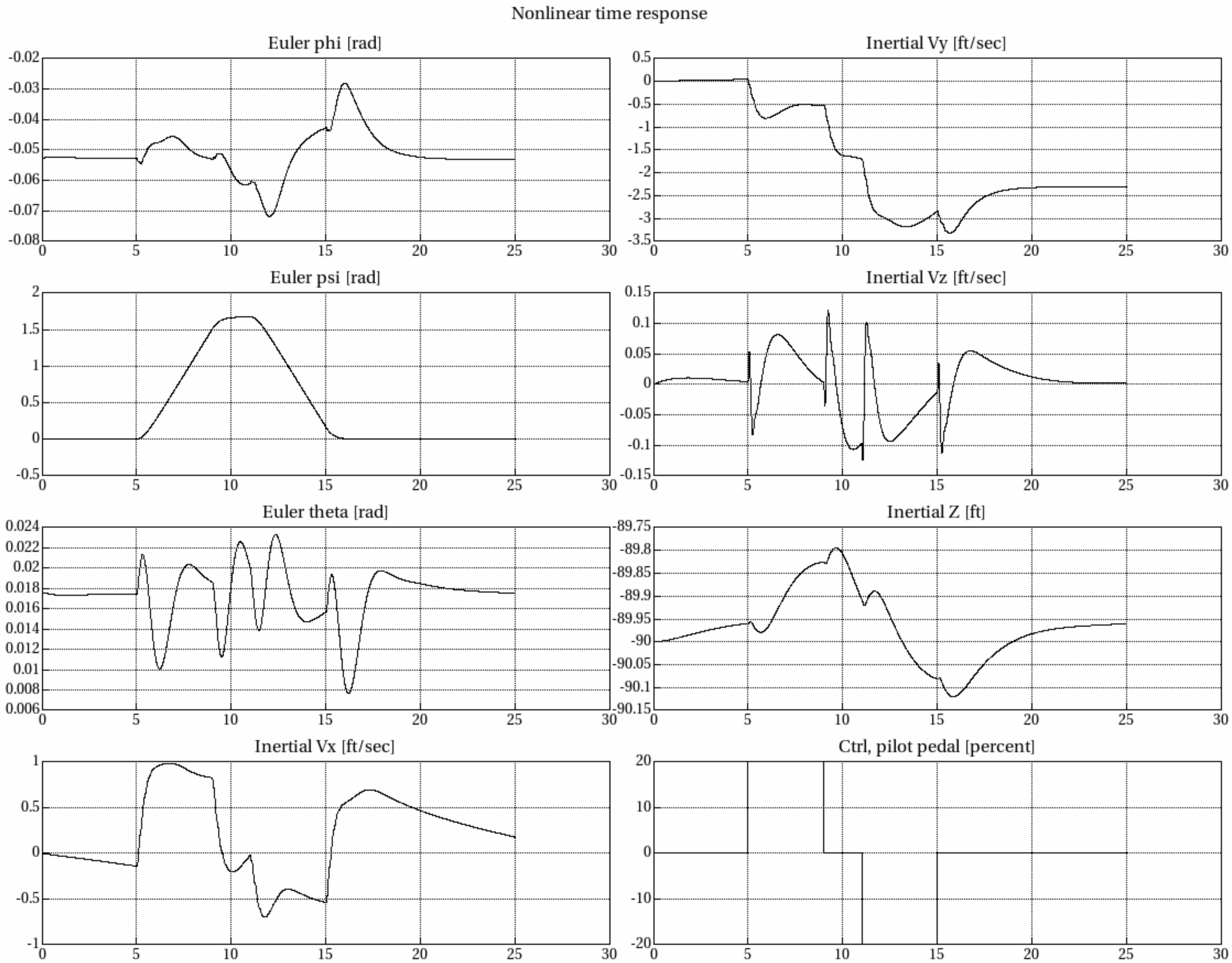


Figure 2 Utility Helicopter Simulation Responses with Inner Loop DI CLAW – Pedal Doublet, Hover

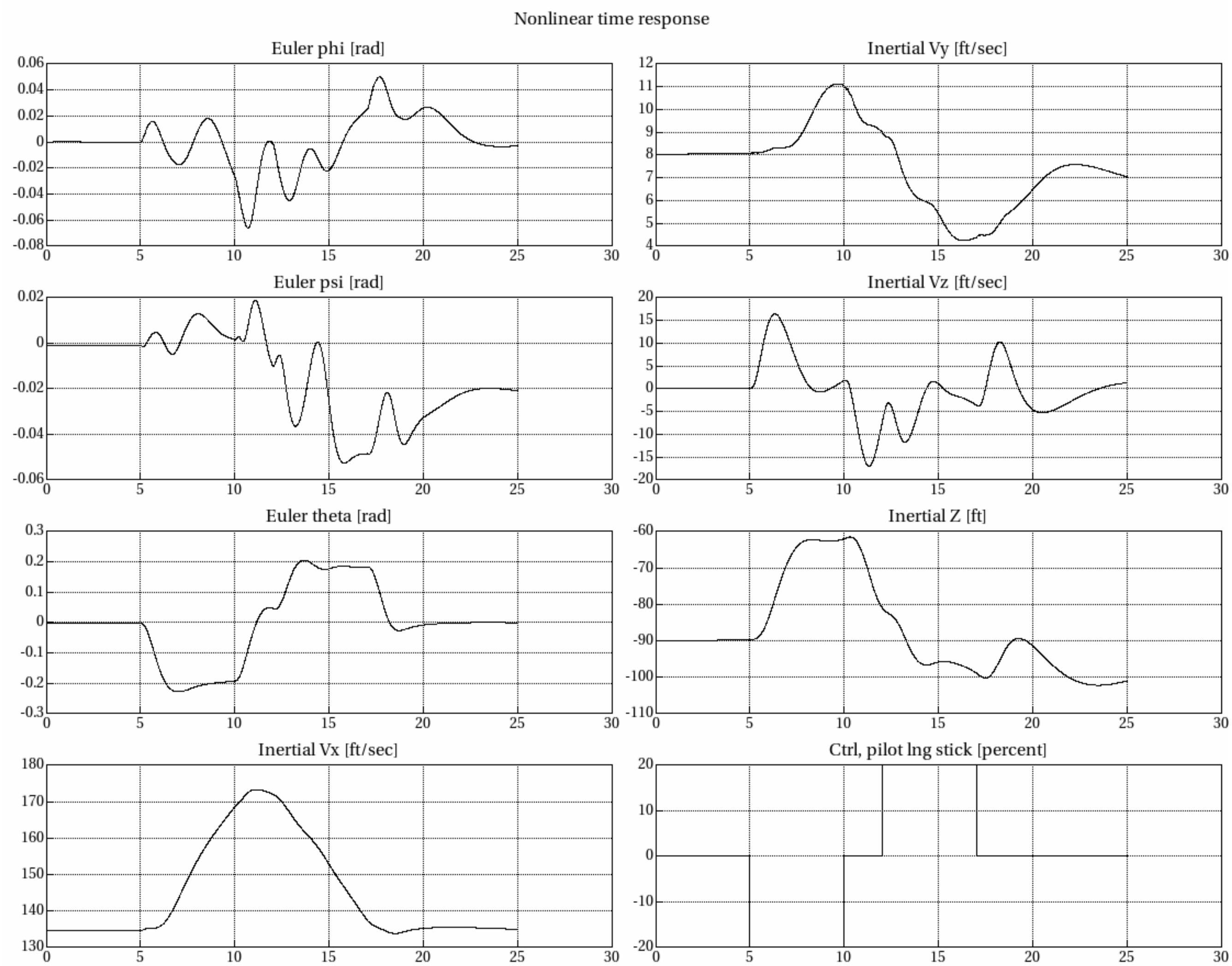


Figure 3 Utility Helicopter Simulation Responses with Inner Loop DI CLAW – Long. Doublet, 80 knots

Task 5 – Deck Motion Prediction Algorithm

During the previous reporting period, efforts were made to implement a dynamic forecasting method, a Holt-Winters (H-W) method. In implementation, a multi-block method was used where the data were organized in multiple sampling blocks with offsets. The H-W algorithm was then applied to each data block with adaptation to generate the forecasting for that block. Although it provides a reasonable prediction for a short amount of future time, the algorithm had difficulty predicting a longer time period due to the requirement of "seasonal cycle" input which defines the deterministic trend term of a given signal. Since the ship motion is an inherently random process (even though a set of dominant periods can be extracted), the H-W algorithm may not be the best choice for the current task. Therefore, efforts were made in this reporting period to investigate an alternative method, a minor component analysis (MCA) method.

The minor component is the direction in which the data has the smallest covariance. The statistical method for extracting a minor component from the input data is called minor component analysis. The MCA determines the directions of smallest variance in a distribution. They correspond to the directions of those eigenvectors of the

covariance matrix of the data which have the smallest eigenvalues. The main idea of MCA was applied for a curve fitting problem (Oja 1992). Usually, the least squares method is used to solve such problems. For example, given a set of data points ($\mathbf{x_1}$, $\mathbf{x_2}$), the problem of having a line model to fit the data in the usual least square sense becomes the problem of finding a pair of estimates. If it is assumed that only the measurements $\mathbf{x_2}$ contain errors while the measurements $\mathbf{x_1}$ are accurate, the total least squares approach gives the optimal way to minimize the sum of the squared lengths of all the bars which are perpendicular to the estimated line. The total least squares fitting problem can be reduced to the problem of finding the minimum eigenvalue and its corresponding normalized eigenvector of matrix or, in other words, finding the first minor component of the data set.

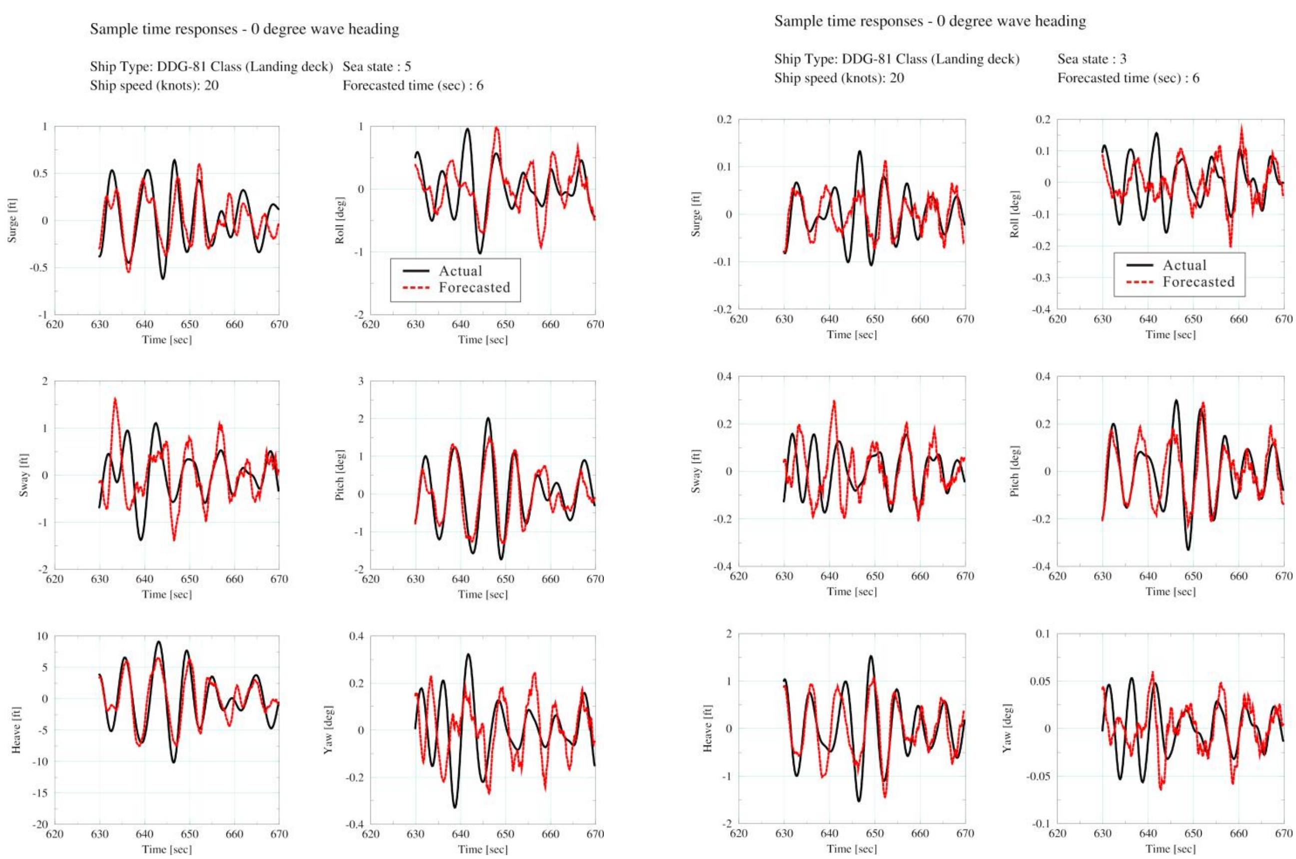
To implement the MCA method, a set of ship motion data is aligned into a sequence of vectors, $\boldsymbol{X_i}$. The eigenvalues and eigenvectors of the autocorrelation matrix, $\boldsymbol{R}= \sum_{i=1}^{N} X_i X_i^T$, can then be calculated. The vector $\boldsymbol{X_i}$ is formed as $[\boldsymbol{X_{1i}}, \boldsymbol{X_{2i}}]^T$. where $\boldsymbol{X_{1i}}$ is the measured ship motion and $\boldsymbol{X_{2i}}$ is the forecasted motion in the length of the forecasting window. Based on the MCA algorithm, the forecasted vector ($\boldsymbol{X_{2i}}$) is calculated using an approximated equality formulation consisting of eigenvectors which are associated with the smallest eigenvalues of the autocorrelation matrix ($\boldsymbol{R}$).

For simulation tests of the MCA based ship motion forecasting algorithm, a set of ship motion data is required. Although it is best to used measured ship deck motion data for the simulation tests, the ship motion outputs from USN SMP and STH are used for the current research because of a lack of measured data. The full 6-DOF motion (surge, sway, heave, roll, pitch, and yaw) is considered in response to the variation of the sea state wave conditions, the wave heading angle, and the ship speed. Given a sea state, ship speed, and wave heading angle, the ship motion is generated by sweeping the significant wave height and the wave modal period over the range as defined by a sea state table. For this research, two classes of ship model, DDG-81 class and LHA class, were used to generate the ship motion data. A total of 1,260 test cases were generated for each ship class. Each set of test conditions is a combination of (a) three sea states (3, 5, and 6), (b) two ship speeds (10 and 20 knots), (c) ten wave heading angles (0, ±30, ±60, ±90, ±135, ±180 degrees), (d) five significant wave heights for each given sea state, and (e) four wave modal periods for each given sea state. The significant wave heights and the wave modal periods were arbitrarily selected from the NATO Sea State Numeral Table for the Open Ocean North Atlantic in order to simulate a greater variety of ship motions.

The 6-DOF landing deck motions were sampled at a 10 Hz rate for each test case. It should be noted that Landing Spot 8 was used for the LHA class ship. The current MCA based ship motion forecasting algorithm was set to predict the deck motion up to 6 seconds ahead considering the accuracy and computational complexity. Further research will be required to enhance the overall performance. About the first 1,500 points of deck motion data were used for the MCA algorithm training and the remaining 8,500 points were used to test the proposed forecasting algorithm. The minor components of the autocorrelation matrix were selected in a sense that their energy added up to no more than 1% of the total energy. Figure 4 shows the sample time history comparison with 6 seconds of forecasted values of the DDG-81 class ship for the following cases: sea states 3 and 5, a ship speed of 20 knots, and a wave heading angle of 0 degrees. The black solid lines represent the actual ship motions and the red dashed lines are the forecasted values.

In order to provide a quantified performance criteria, several statistical terms were used. From the initial testing, it was observed that the forecasting error variations in terms of standard deviation are very close to a normal distribution. Thus, a range of forecasting error was calculated such that the forecasted deck motion was within 90% of its real value. For example, if a range of forecasted error is wide, then the forecasting performance is not acceptable. In addition, the significant amplitude, which is based on a concept similar to the significant wave

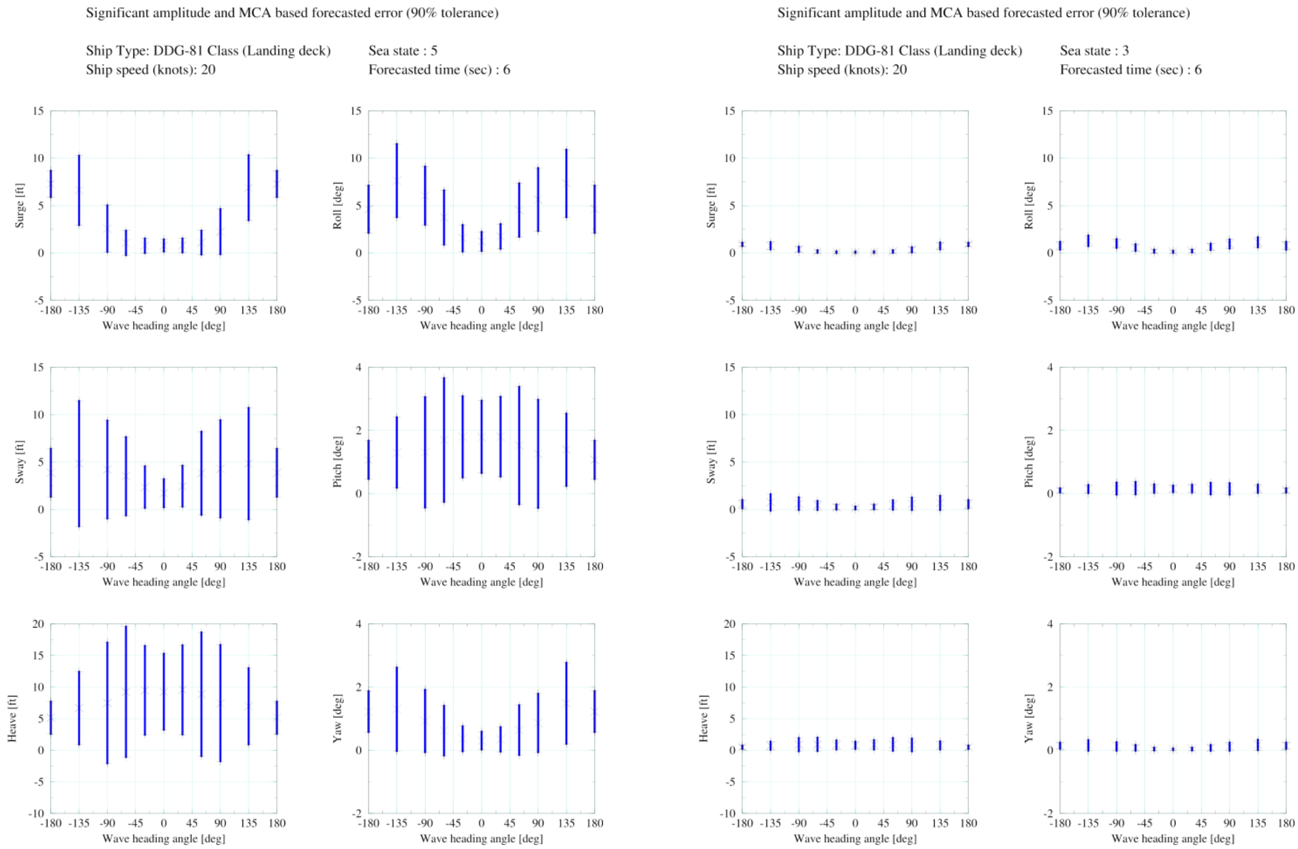
height, was defined to represent the nominal level of ship motion. The significant wave height is a statistical term that represents the average of the highest 1/3 of the waves in a given wave train. Since it is known that about 16 percent of the waves will be higher than the significant wave height, it is suitable to illustrate the sea condition. Similarly, the ship motion can be quantified using the significant amplitude (e.g., significant heave, significant roll, etc.). Figure 5 shows the corresponding quantified performance of the forecasting algorithm for the same simulation condition. Figure 6 shows the simulation results using an LHA class ship for the same simulation condition. It can be seen that the forecasting error increases when the sea wave heading angles are close to the port and starboard sides of ship due to the highly coupled roll and pitch motion. This is because of the loosened correlation of the matrix $\boldsymbol{R}$. In fact, one of the default procedures of helicopter shipboard landing is to align the ship with respect to the wave heading angle. From the figures, the MCA forecasting algorithm forecasted the ship motion reasonably well for wave heading angles between ±45 degrees, which satisfies the requirements of the current task. In addition, it can be observed that the forecast algorithm performs very well for relatively smaller ship motions, such as low sea state condition and heavier ship. It should be noted that the forecasting accuracy is significantly improved for shorter forecasting time and it is useful for a deck motion feedback controller (see Figure 7).



(a) sea state : 5

(b) sea state :3

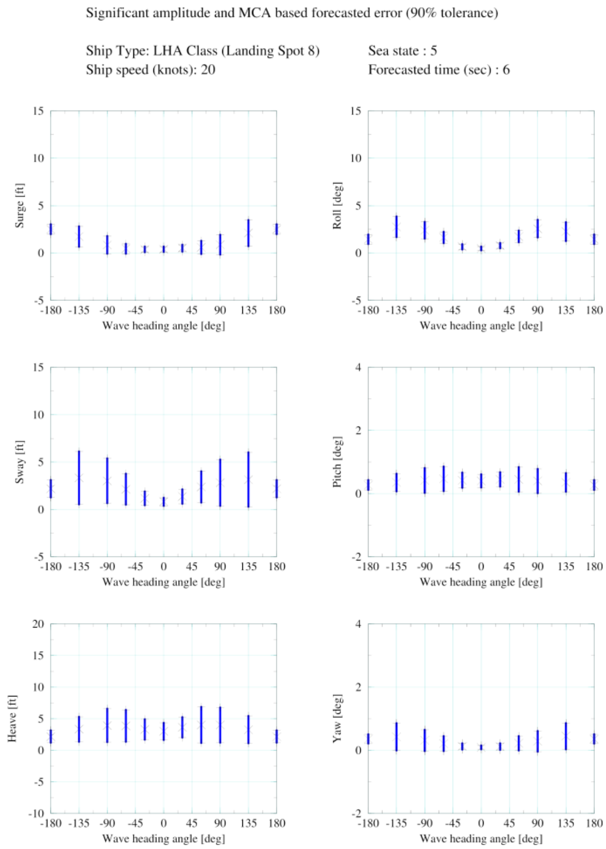
Figure 4 Comparisons of time responses of forecasted 6-DOF ship motion (DDG-81 class)



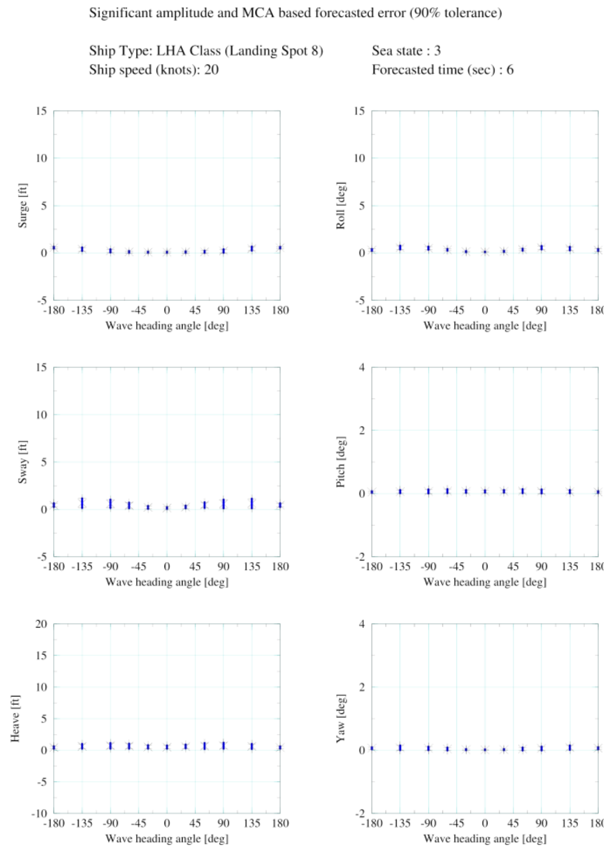
(a) sea state : 5

(b) sea state : 3

Figure 5 Quantified performance criteria (vs wave heading angle) - DDG-81 class

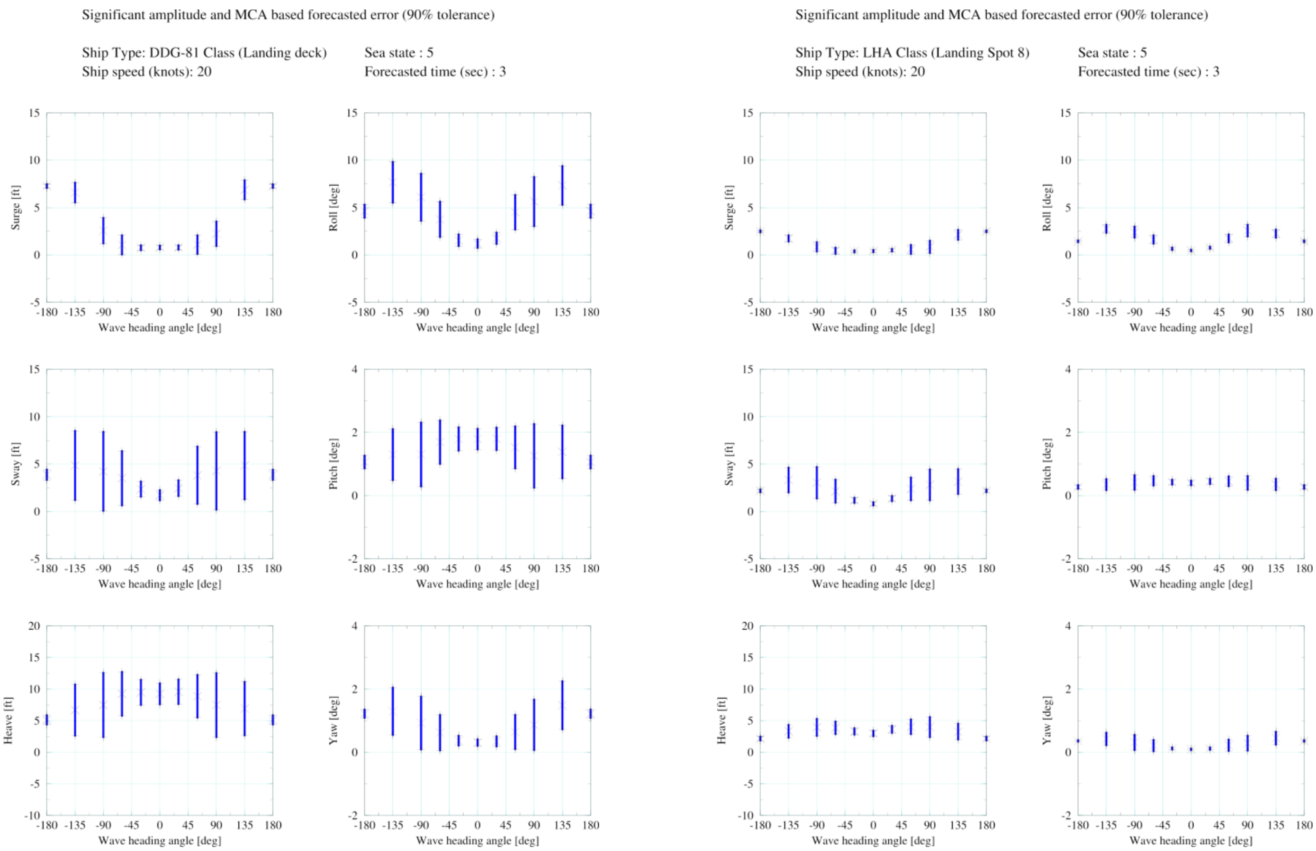


(a) sea state : 5



(b) sea state : 3

Figure 6 Quantified performance criteria (vs wave heading angle) - LHA class



(a) DDG-81 class

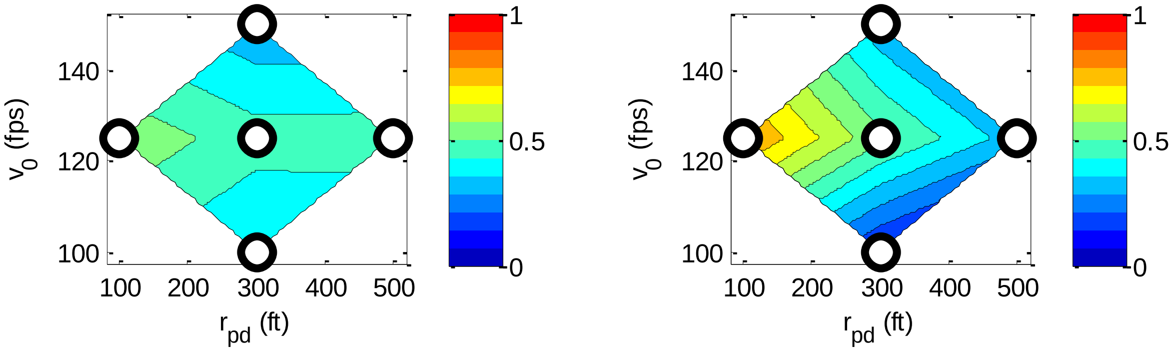
(b) LHA class

Figure 7 Quantified performance criteria for 3 second forecast

Task 6 - Path optimization of shipboard helicopter:

On the path optimization front, the team is ready to move forward with the first path optimization study. This study involves: (i) the mathematical description of a spatially and temporally-varying approach profile using a design vector, $\mathbf{X}$, (ii) the development of a novel objective function, $F(\mathbf{X})$, that serves as a quantitative assessment of the approach performance, and (iii) mathematical constraints, $g_j(\mathbf{X})$, which are imposed to ensure that the optimization results are operationally feasible and safe.

The details of the formulation were described in the previous progress report, and work in the past quarter focused on the development of alternative objective functions. The overall performance for a given approach trajectory can potentially be influenced by a number of independent and interdependent performance factors, such as: 1) the maneuver duration, 2) the power requirements over the course of the maneuver, 3) path error along the maneuver, and 4) the effects of the turbulent ship airwake. Research to date has focused on the integration of these factors into a single objective function. While the simplest objective function can be constructed by applying equal weighting to all performance factors, alternative objective functions may be constructed with varied relative weights between the different performance factors (see Figures below). The representative results [from our abstract] shown here are based upon a simple sensitivity study that will be extended for a full optimization in the coming quarter.



a) $F_{app}(X_{temp})$ a) $F_{app}(X_{temp})$

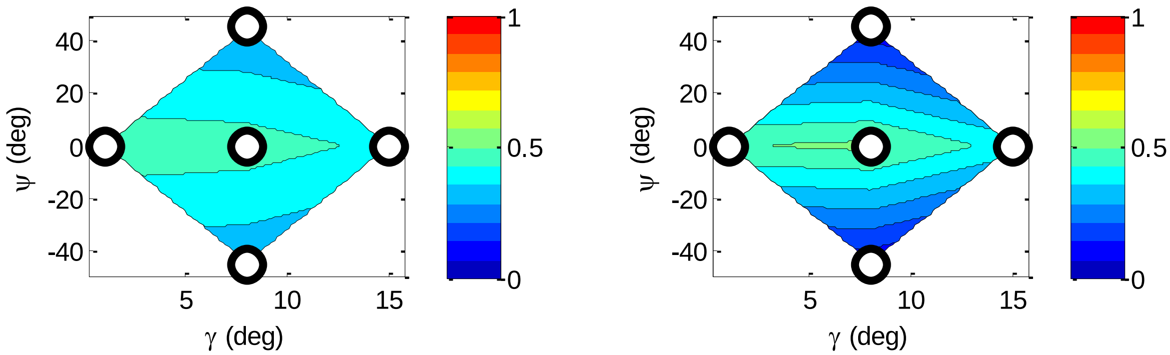


Figure 8 Sensitivity Study of a Weighted Performance Index for Automated Ship Approaches (These contour plots show the proposed weighted cost function for the automated ship approaches presented in the previous progress report, the cost is a function of the approach azimuth, glide slope, initial velocity, and aggressiveness of deceleration).

3. Significance of Results

The deck motion forecast method was established using the MCA algorithm and was tested for various conditions which were combinations of multiple sea states, ship speed, wave heading angle, significant wave height, and average wave modal period. The simulation results identified the capability of the MCA based ship motion forecasting algorithm by providing a forecast confidence measurement in terms of a statistical interpretation of the prediction error.

Implementation of the DI Controller in CSGE / Flightlab has so far been successful. The design scripts are automated so that implementation for UAV and H-53 class rotorcraft can be performed very quickly (just a few hours work to integrate and run inverse model generation for preliminary implementation, followed by a week of work for testing and tuning).

4. Plans and upcoming events for next reporting period

Task 1 – Plant Model and Disturbance Models: The FireScout and H-53 class FLIGHTLAB models will be developed and distributed to team members.

Task 4 – Dynamic Inversion Control Design: Will complete implementation and testing of outer loop DI

CLAWS. A preliminary version of the CLAWS will be transitioned to counterparts at NAVAIR and NSWCCD,

Task 5 – Ship Motion Prediction: Next effort will be focused on the MCA algorithm enhancement to improve the accuracy.

Task 6 - Path optimization of shipboard helicopter: Continue with a full path optimization study following the plan in our AIAA draft manuscript. We are also likely to continue path optimization work using our Flightlab simulation once it is complete (as opposed to the GENHEL simulations used to date).

5. References

Oja, E.,``Principal Components, Minor Components, and Linear Neural Networks," Neural Networks, Vol. 5, pp.927-935, 1992

6. Transitions/Impact

Results were presented at the SBA program 2014 year-end review at Carderock.

7. Collaborations

Penn State and ART have collaborated directly with John Tritschler at NAVAIR. In addition, we are communicating with other Navy researchers pursuing similar projects: Al Schwarz at NSWCCD who is investigating ship motion prediction and AutoLand, and Dave Findlay at NAVAIR who is investigating advanced control laws for shipboard landing. We have discussed transferring the DI control laws (in FLIGHTLAB CSGE format) to Al Schwarz. This is planned for February 2015.

8. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Junfeng Yang, a new PhD student at Penn State started in January 2015.

9. Publications

Tritschler, J.K. and Horn, J.F. "Objective Function Development for Optimized Path Guidance for Rotorcraft Shipboard Recovery" Draft manuscript submitted to the 2015 AIAA Atmospheric Flight Mechanics Conference (AIAA AVIATION 2015). Expected notification of acceptance in March 2015.

10. Point of Contact in Navy

Michael P. Fallon
Naval Air Systems Command Code 4.3.2.4
Flight Dynamics
michael.fallon@navy.mil
301-342-7890 (Voice)

11. Acknowledgement/Disclaimer

This work was sponsored by the Office of Naval Research, ONR, under grant/contract number N00014-14-C-0004. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Office of Naval Research, or the U.S. government.

Section II: Project Metrics

Contract # N00014-14-C-0004

Autonomous Control Modes and Optimized Path Guidance for Shipboard Landing in High Sea States

Progress Report (CDRL A001)

Progress Report for Period: July 9, 2014 to October 9, 2014

PI: Joseph F. Horn
814-865-6434
joehorn@psu.edu
Penn State University

Co-PI: John Tritschler
(301) 995-1637
john.tritschler@navy.mil
AIR-4.3.2.4

Co-PI: Chengjian He
(408) 523-5100
he@flightlab.com
Advanced Rotorcraft Technologies

October 31, 2014

1. Metrics

Number of faculty supported under this project during this reporting period: 1

Number of post-doctoral researchers supported under this project during this period: 0

Number of graduate students supported under this project during this reporting period: 0

Number of undergraduate students supported under this project during this period: 0

Number of refereed publications during this reporting period for which at least 1/3 of the work was done under this effort: 0

Number of publications (all) during this reporting period: 0

Number of patents during this reporting period: 0

Number of M.S. students graduated during this reporting period: 0

Number of Ph.D. students graduated during this reporting period: 1

Awards received during this reporting period: 0

Invited talks given: 0

Conferences at which presentations were given (not including invited talks above): 0

2. **Financial information**

FY 2014	Total Budget	Obligated This Period	Obligated Cumulative	Expended This Period	Expended Cumulative	Grant/ Contract Period of Performance
6.2 (Applied Research Funding)	**$245,000**	**$245,000**	**$245,000**	**$ 68,850**	**$83,909**	**July 9 ,2104 to July 8, 2015**

3. **Administrative notes and other items of interest**

None.